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TITLE: THE HISTORY OF GAMMA-RAY BURST OBSERVATIONS

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THE HISTORY OF GAMMA-RAY BURST OBSERVATIONS

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Abstract

Cosmic gamma-ray bursts have been observed for 1-1/2 decades since their fortuitous discovery by nuclear test detection instruments flown on the Vela satellites. Although the volume and detail of data available through these observations has considerably refined our knowledge of the characteristics of these events, there is no confident identification of source objects or reliable model of the processes involved. The observations do suggest, however, that the bursts originate at neutron stars (probably highly-magnetized neutron stars).

INTRODUCTION:

The history of gamma-ray burst (GRB) observations spans 1-1/2 decades since the publication of the original discovery paper in 1973.[1] Actually, the observations span more than two full decades since the event was recorded, on 1967 July 2 (designated as GB670702, signifying decade and year, month, and day of the observation), which led to the initial discovery of the phenomenon. This event exhibited a distinctive temporal structure consisting of a short pulse of fractional-second duration followed by a second pulse of several seconds duration.[2] Records of the event returned by the two individual Vela IV instruments show remarkably good agreement. Since the satellites were separated by about 240,000 km, with one satellite located within the earth's magnetosphere and the other outside the bowshock, this is evidence that the event was electromagnetic in nature and not due to charged particles. Figure 1 displays the records of the event returned from both satellites, shown superimposed and differentiated by opposite hatching.

The records of this event were discovered as the result of the first search for any data which were recorded in near coincidence by the two individual Vela IV satellites. The earlier Vela III satellites carried a similar, but somewhat more primitive, gamma-ray detection system, but the Vela IV data were the first for which the times the event occurred (recorded as an independent spacecraft-clock time) were converted to a standardized time (UT). These instruments were designed to detect the delayed fission gamma radiation from a nuclear explosion hidden behind a deployed shield or a natural shield such as another planet, as the fission debris expanded from behind that shield. The instruments were known to respond to local effects, primarily charged particles trapped within the magnetosphere. The events provided a background obscuring the presence of GRB's. The search was conducted anticipating that there were no natural phenomena capable of stimulating, in near coincidence, the various nuclear-test detection instruments designed to respond to rapidly-rising signals. To our surprise, however, several nearly coincident events were found in data from the gamma-ray detection systems. Only the one event, GB670702, was intense enough to exhibit a distinctive temporal structure. The temporal structure was not characteristic of that expected of decaying debris from a nuclear detonation, thus, there was little concern that the observed response was an indication that nuclear weapon testing was being conducted in space.

At the time that these data were found, the Vela V satellites were already in the final preparations for launch, and it was anticipated that data from these systems would soon be available. However, an electronics problem in Vela V created an even greater contribution of artificially generated records to be analyzed, and there was even greater need of an automated procedure to search the separate datasets for events occurring in near coincidence. By the time the database had been prepared and software developed to locate these events, both Vela V and Vela VI satellites were operating on orbit. These four satellites provided a database which yielded evidence of a dozen events once the processing software was successfully tailored. They also continued to operate and return data until they were turned off in 1984.

TEMPORAL STRUCTURE:

Gamma-ray burst exhibit a wide range of characteristics in their temporal structure, with the best description being "chaotic." Durations ranged from tenths of a second to tens of second, but most often included multiple peaks of intensity. The Pioneer Venus Orbiter Gamma-Burst Detector (PV/OGBD, or PVO) was designed to better record details of the temporal structure of these events, and has observed events displaying an even wider range of temporal characteristics. Figure 2 shows the briefest event observed to date.[3] Even the superior resolution of the PVO instrument was not able to resolve the structure of this single spike which has a duration of only about 20 ms. Another brief event, GB841215, exhibits at least seven statistically significant peaks[4] in the record from International Cometary Explorer (ICE) shown in Figure 3, although the duration of the event is only 0.3 s. The rise time of these short bursts certainly limits the size of the emitting region to about 1000 km, which is consistent with the scale of compact objects.

In contrast to these brief events, Figure 4 shows the PVO response for the longest duration burst observed to date.[5] Although the total capacity of the PVO high-resolution memory is only 28 s, data are also received with poorer (and variable) time resolution through the real-time (RT) telemetry. This RT record for GB840304 shows an event consisting of two major peaks spanning about 200 s, followed by a slowly decaying emission extending to at least 1000 s. This decaying emission does not exhibit evidence of cooling; the spectrum remains as hard as that of the initial outburst. (It is not clear that the long duration of this event identifies it as being anomalous, however even the 200 s spanned by the two major peaks establishes it as the longest event observed to date.) It is difficult to conceive mechanisms which are able to remain intact through seconds of time while producing the intensities and hard spectral qualities exhibited by gamma-ray bursts, but it is particularly difficult to extend those mechanisms to times of 1000 s.

Although many GRBs show recurrent patterns in structure suggestive of periodicity, a critical evaluation of the data almost invariably has demonstrated that the emission fails to repeat at a precise interval and a claim of a periodicity is unwarranted. The single exception is GB790305, which exhibited a clearly significant 8 s periodicity during sustained emission over an interval of 140 s following the initial, intense outburst,[6] as shown in Figure 5. This phenomenon may be more common, but observable only for this event, because of its unusually high intensity. The 8 s period has been suggested as a modulation induced by the slow rotation of an old neutron star.

GAMMA-BURST SPECTRA:

The Vela gamma-ray instruments did not provide any spectral resolution of the radiation observed in these events, since the measurements were made in a single differential interval of either 150 to 750 keV or 300 keV to 1.5 MeV (energy deposited in the scintillator). Because the measurements were made within the energy region commonly accepted as a definition of gamma radiation, it was clear that the bursts were quite hard. They were thus given the name "gamma-ray bursts" The first definitive measurements of the spectral character of the bursts were made from IMP-6 and IMP-7 data.[7] These data had been recognized as being significant even before the announcement of the Vela discovery of the phenomenon, because they exhibited similar, very hard spectra. The data for a number of events were all able to be fit with a single function; a 150 keV exponential, as shown in Figure 6.

The fortuitous observation of a gamma-ray burst during the flight of Apollo 16 allowed a definitive analysis of the spectral distribution.[8] The data from the gamma-ray spectrometer were able to be fit well with an optically-thin thermal bremsstrahlung (OTTB) function, with some relativistic corrections. The burst source was within the field-of-view of the x-ray spectrometer as well, and these data are also consistent with an extrapolation of the fit to the gamma-ray data, as shown in Figure 7. The KONUS experiment flown on the Soviet Venera spacecraft have measured the spectra of a large number of bursts.[9,10] These too are generally well fit by an OTTB (but without application of relativistic corrections in this analysis) as shown in Figures 8 and 9.

Even though an OTTB function fits the data very well, it can not be the actual production mechanism unless the sources are very near. Thermal synchrotron emission can also be fit about equally well to the data, but neither function can adequately describe the high-energy tail that has been observed for a number of events by the Gamma-Ray Spectrometer (GRS) instrument flown on the Solar Max. Mission (SMM).[10] A composite of several power-law functions also fits the data but also fails to directly suggest a burst mechanism.

SPECTRAL FEATURES:

The KONUS data also revealed the first evidence of features in the spectra of gamma-ray burst which were proposed to be "lines."[11] These lines took two forms; absorption features ("dips") occurring at energies below 100 keV, and emission features at 400–450 keV. Examples of both are shown in Figures 8 and 9. The absorption features have been suggested to be generated by a cyclotron absorption process, implying a high magnetic field. The emission features have been attributed to annihilation radiation, red-shifted in a strong gravitational field. These observations support a consensus that a highly magnetized neutron star is the environment in which the burst is generated.

The nature of the response functions of instruments used to observe these bursts is such that there is some question regarding the validity of these interpretations of the data, because of uncertainties in the reconstruction of the incident spectrum from the observed response.[12] Few gamma-burst instruments have investigated the energy region below 100 keV, and few chance observations have been found because of the inherent limitation in the fields-of-view possible at lower energies. In view of the potential importance of this observation, it was felt to be necessary to be able to critically measure the spectral character of gamma burst in this spectral region. Thus, the Ginga Gamma Burst Detector (GBD) instrument was designed to cover the energy range 2-400 keV with a single, integrated instrument. (Note: Just following this conference, on 1988 Feb. 5, the Ginga GBD observed "the" event for which it was designed, with spectral structure which may represent 1st and 2nd harmonic cyclotron resonance.)

SOURCE LOCATIONS:

The Vela system consisted of an array of satellites distributed in an orbit of 120,000 km radius. This array provided a maximum of 0.8 s separation at the speed of light, and absolute timing for events with a resolution of about 20 ms. Thus, there existed a capability to define the location of the source of an event through time-of-flight analysis of the burst wavefront arrival. The best accuracy achievable from these data was on the order of several degrees, which was not sufficient to identify candidate source objects or to direct searches from optical or other data. The locations were adequate, however, to eliminate the sun and other major members of the solar system as possible source candidates. Although few in number and not precisely resolved, the distribution of these locations was consistent with isotropy,[2] as illustrated in Figure 10. This isotropy was confirmed by subsequent measurements by the KONUS experiment[9] and by results utilizing the time-of-flight technique.[13]

Since these events occur infrequently and unpredictably in either time or location, it was clear that systems intended to determine their characteristics would have to be omnidirectional (or at least wide angle) and nearly continuously active. It was apparent that the time-of-flight technique was the most suitable means of providing locational information within these constraints and with the limited availability of resources. The obvious approach to improving the resolution of location was to simply increase the baseline between observing platforms. Figure 11 shows the effective angular resolution which can be achieved by this technique as a function of separation and precision in absolute timing. It can be seen that with the level of precision in timing that had already been achieved, separations on an interplanetary scale would allow locations to be defined with angular precision on the order of tens of arc-seconds; possibly sufficient for identifying a specific counterpart candidate through searching archived data or implementing directed searches at optical or other wavelengths.

A network of observing platforms is necessary to determine a source location using the time-of-arrival technique. A minimum of three observations is necessary to provide a location in two dimensions, and a fourth observation is necessary to remove the ambiguity that is equivalent to a mirror image. Such a widely-spaced array was established with the launch of the Helios-B satellite, bearing a NASA/GSFC gamma-burst instrument in 1976, the Pioneer Venus Orbiter, the Soviet Venera satellites, and the International Sun-Earth Explorer-3 launched in 1978, and the Vela and Prognoz satellites in near-earth orbits, as shown schematically in Figure 12. This network was in place to observe the dramatic event GB790305. This event was observed by 11 experiments on 9 different satellites and yielded a very precise determination of source location.[14] This location was found to be in the direction of the supernova remnant N49 in the Large Magellanic Cloud, located at 55 kparsec, as shown in Figure 13. Although this suggested association was exciting, the fact that the distance would imply a total energy of 10^{45} ergs in the gamma-ray region alone has caused a major part of the astrophysical community to reject the identification, instead assuming a foreground object to be the source of the burst.

Typical of subsequently determined locations falling in uncrowded fields, the region defined for GB790406 was found to be empty of objects brighter than 22nd magnitude from a survey of archive plates,[15] as shown in Figure 14. Subsequent deep-sky searches disclosed objects of magnitude 22-24 within the error box. Also, searches of the source location defined for GB781119 were conducted from optical, x-ray and radio data. At most, marginally significant results were obtained, excepting the identification of a possible optical transient from archived plates. These results are shown in Figure 15. There have been no solid associations of GRBs with objects observed at other wavelengths.

OPTICAL TRANSIENTS:

The one area in which there have been exciting positive results in identifying counterparts to GRB's has been the association of optical transients, found recorded on archived plates, with GRB source locations. The first of such was found within the GB781119 source region, and was tentatively identified with a very faint steady-state object found from the deep-sky search. A number of other candidate transients have been found from archival records, but, in most cases, the locations are not quite consistent with what are believed to be conservatively determined error regions. This is true of a short, recurrent transient discovered in near association with the location of GB790325,[17] as shown in Figure 16. Although this observation is tantalizing, the location is removed from the GRB error region to the extent that only an unaccountably large error in the determination of the source location could allow an association between the optical transient and the GRB.

There are several programs which have been implemented to identify and capture records of optical transients as they occur. These have not yet produced any convincing results, however it seems likely that they will be fruitful as capabilities are improved. It is not clear that the optical transients will necessarily be able to be related to GRB's, but they may provide a useful field of study in their own right.

CONCLUSION:

Although the volume of data has been increased tremendously through 1-1/2 decades of gamma-ray burst observations, there is as yet no theory developed which is capable of modelling either the macroscopic mechanism responsible for generating the burst energy or the microscopic emission process. Even allowing that there may be a variety of mechanisms at work, rather than a single mechanism, the complex behaviour exhibited during single events most often defies a facile explanation. The general consensus, based largely upon spectral data, is that the bursts originate at neutron stars. The spectral data and considerations of total energy suggest that the sources lie at maximum distances of several hundred parsecs. This is consistent with the apparent isotropic distribution of source locations but implies a high density of neutron stars within the galaxy, even allowing for frequent recurrence. At any rate, gamma-ray burst astronomy is still a fertile field for those with a passion for wrestling with apparently intractable problems. We can hope that further and more detailed observations will provide enlightenment.

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Figure Captions

Figure 1: The records of the first observed gamma-ray burst event returned from both Vela IV satellites. shown superimposed and differentiated by opposite hatching. The data represent the outputs of digital accumulators, expressed as effective counting rates as a function of time. The vertical extent of the plotted data indicates the resolution available from the coded output of the accumulators. while the horizontal extent indicates the duration of the individual accumulations. Data were continuously recorded with one second resolution before the trigger was effected. and the last four such samples were recorded with the post-trigger event data. Following the trigger. data were accumulated with 1/8 second resolution initially, then incremented by factors of two after each set of four samples was recorded.

Figure 2: The brief event recorded by PVO on 1979 June 13.

Figure 3: The brief. but highly structured event as observed by ICE on 1984 Dec. 15. At least seven statistically significant peaks are observed in a total duration of only 03. s.

Figure 4: The longest event observed to date. from PVO real-time data. The emission extended over more than 1000 s. (The straight line indicates the background counting rate.)

Figure 5: Evidence of 8 s periodicity as observed by the KONUS experiment, following the intense impulsive outburst on 1979 March 5.

Figure 6: The first definitive measurement of gamma-ray burst spectra from IMP-6 and IMP-7 data. All data are fit reasonably well with a common spectra form; a 150 keV exponential.

Figure 7: Definition of the spectral characteristics of a gamma-ray burst observed by the Apollo-16 gamma-ray and x-ray spectrometers. The data are fit well by an optically thin thermal bremsstrahlung function.

Figure 8: Spectral data exhibiting evidence of low-energy spectral absorption. from KONUS data.

Figure 9: Spectral data exhibiting evidence of emission features at 400–450 keV. from KONUS data.

Figure 10: Distribution of location of gamma-ray burst events from Vela data.

Figure 11: Accuracy which can be achieved from the time-of-flight technique of source location. as functions of separation between observing platforms and absolute timing accuracy.

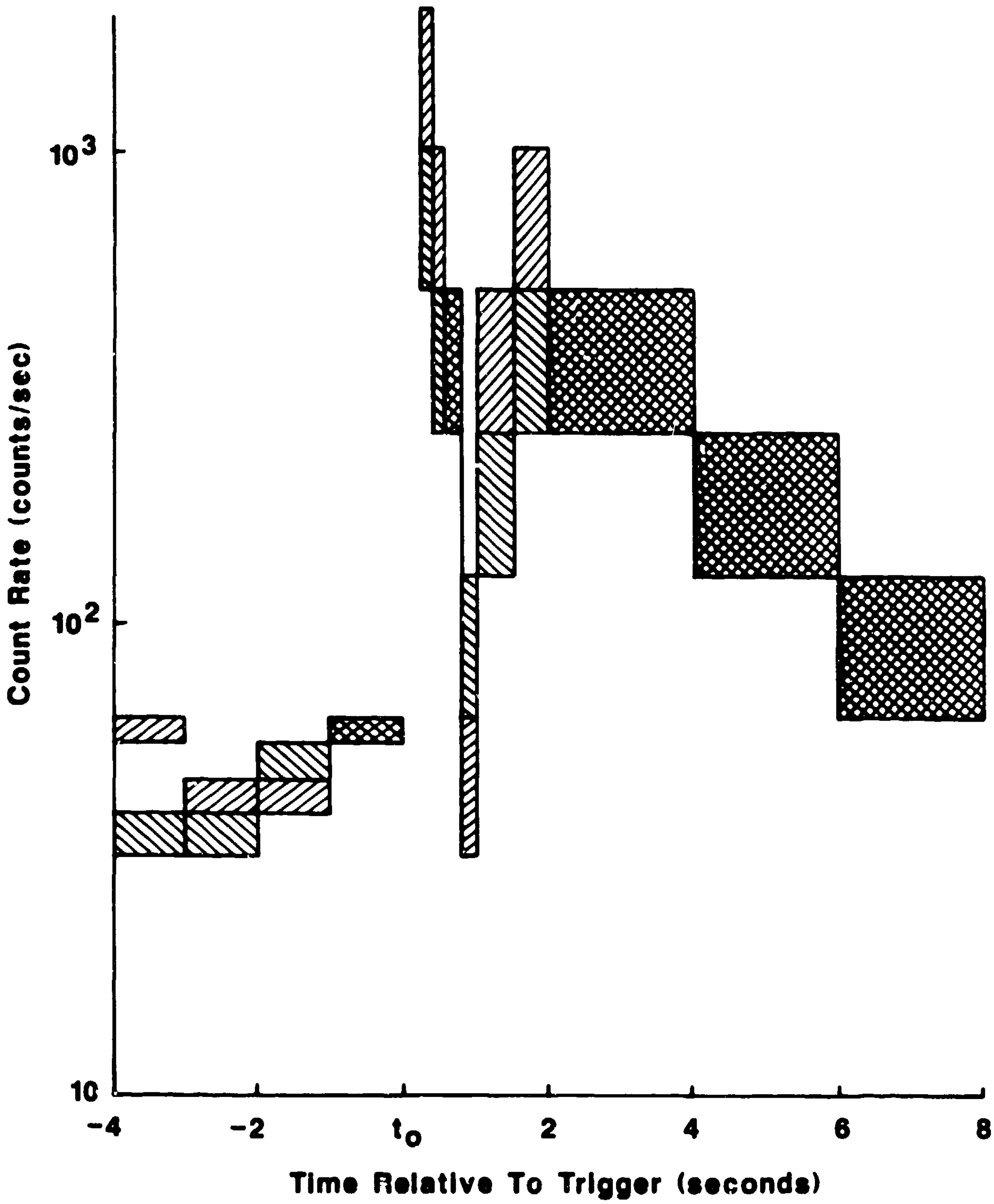
Figure 12: The long-baseline array. as it existed in late 1978 through early 1980 (shown schematically).

Figure 13: The precise location of the 1979 March 5 gamma-ray burst, as determined by the long-baseline array.

Figure 14: The location at the 1979 April 6 gamma-ray burst. No steady-state optical image is found on this archived plate with a limiting magnitude of 22.

Figure 15: The location of the 1978 Nov. 19 gamma-ray burst, including the location of an x-ray source, a radio source, and an optical transient observed from archival plates.

Figure 16. A recurrent optical transient observed from archival plates near the region defined for a gamma-ray burst which was observed 1979 March 25. The top two plates show evidence of a transient object found on plates exposed 28 March 1946 and 31 August 1946. The bottom plate represents the normal configuration of stellar objects, with no identifiable image at that location.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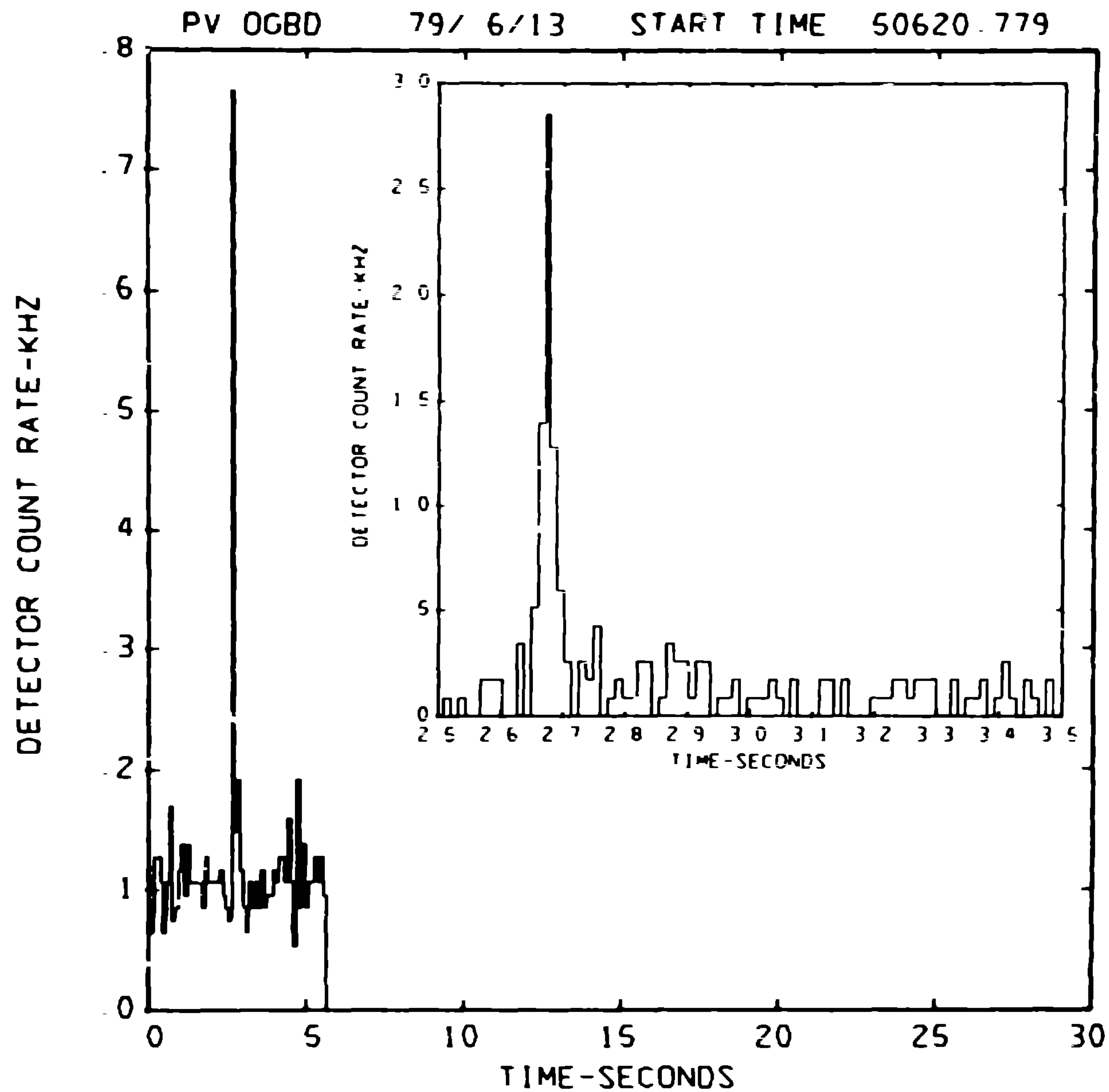
-2
t₀
2
4
6
8
Time Relative To Trigger (seconds)



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TIME-SECONDS
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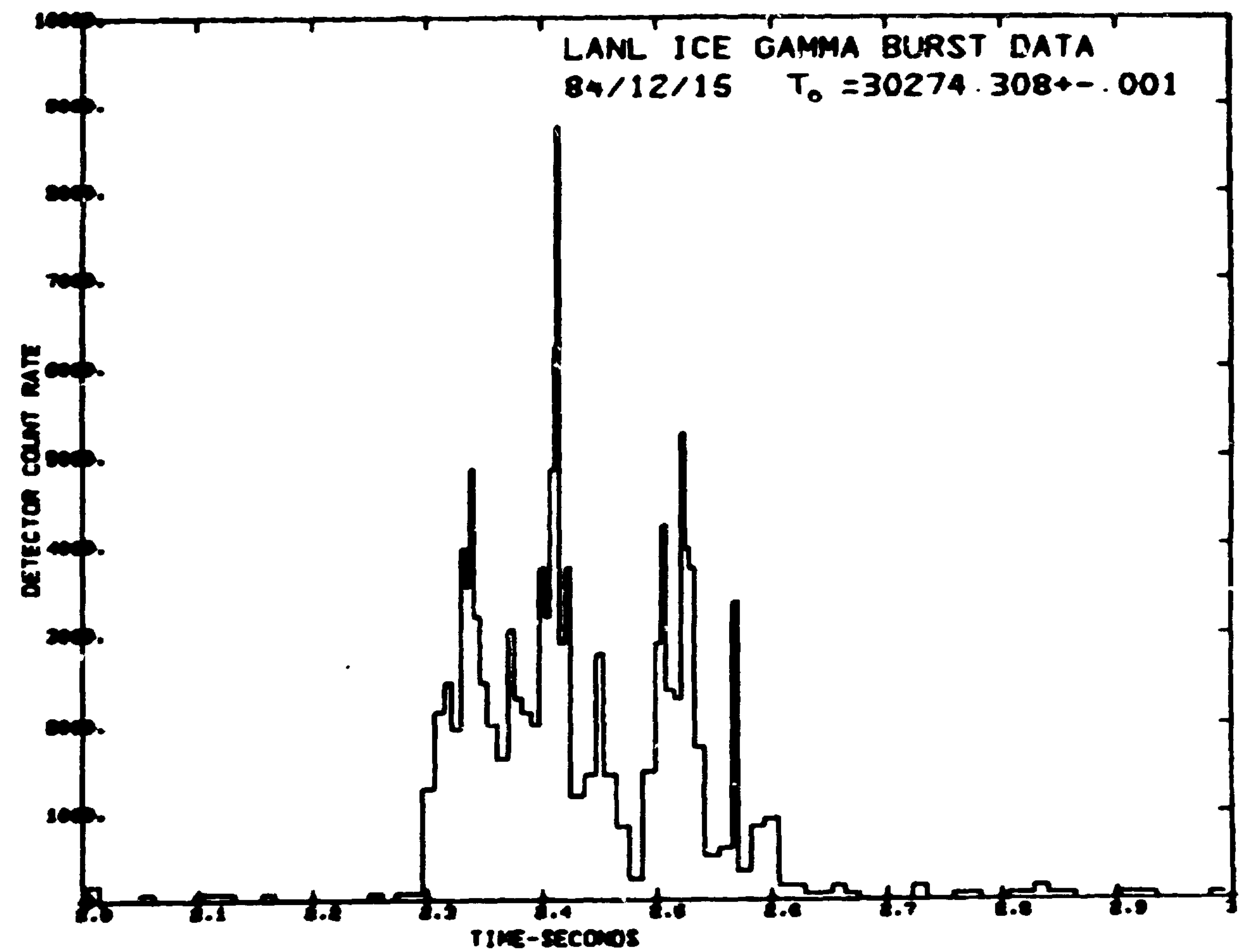
.7
.6
.5
.4
.3
.2
.1
.0
0
5
10
15
20
25
30
DETECTOR COUNT RATE-KHZ
TIME-SECONDS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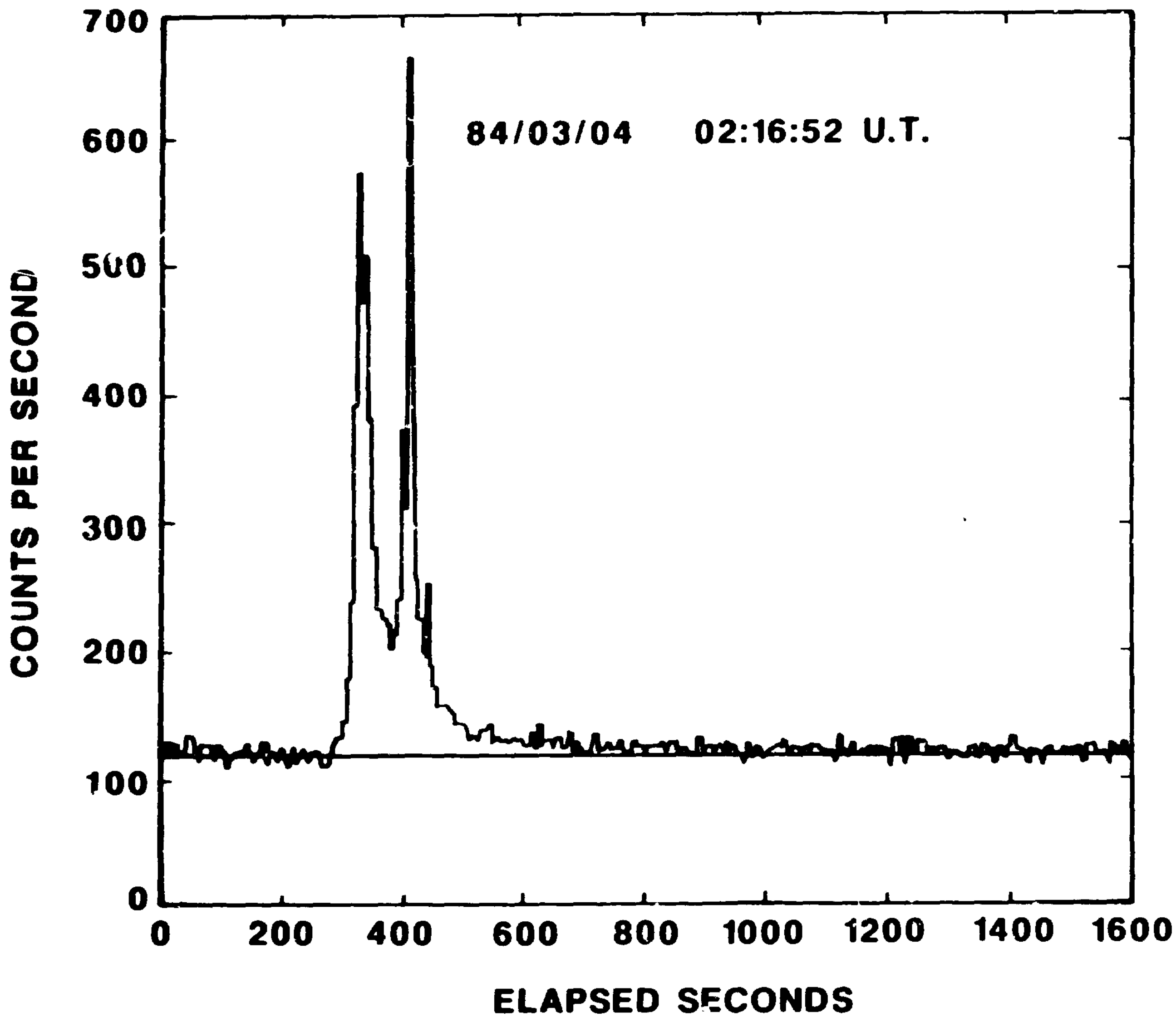

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1000
1200
1400
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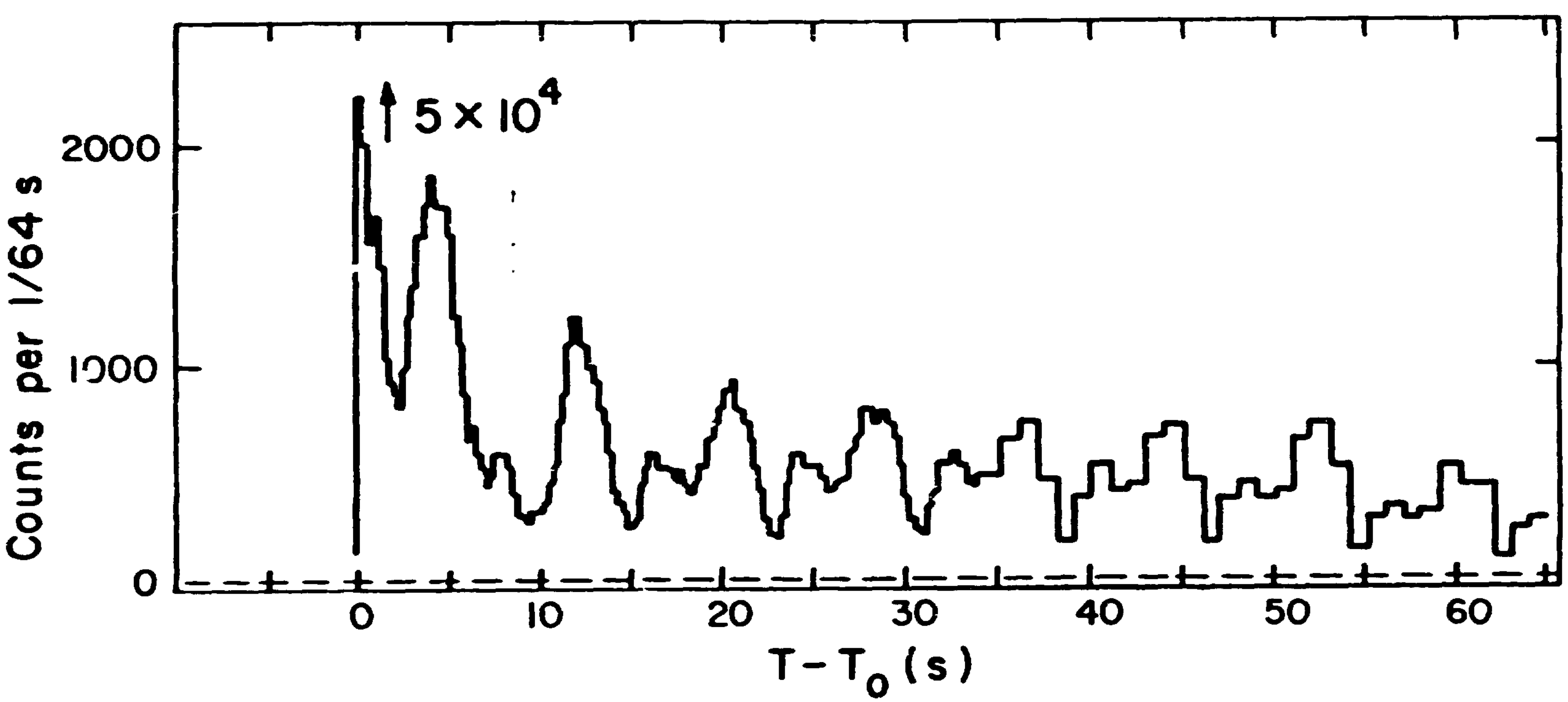

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40
50
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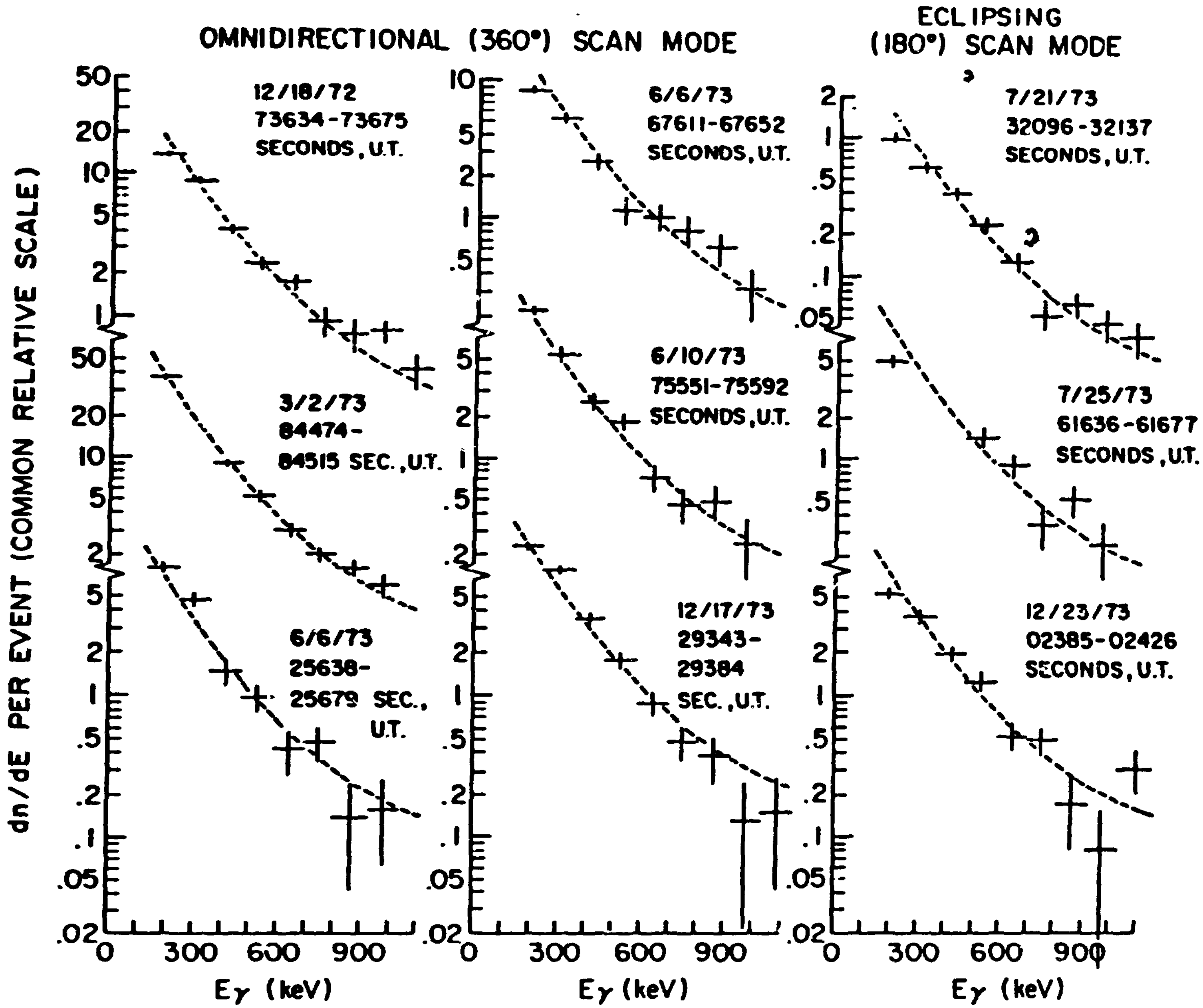
T − T0 (s)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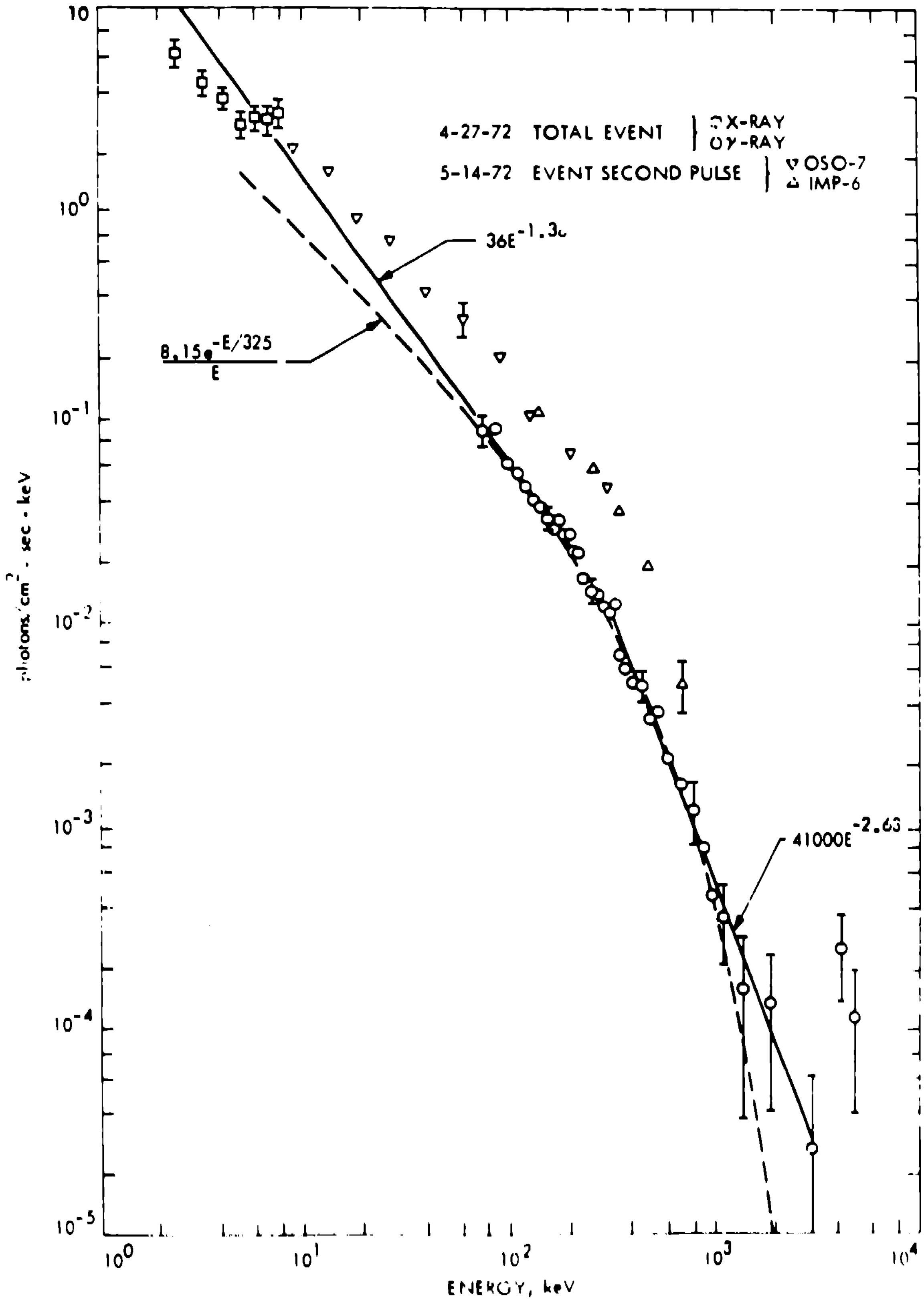
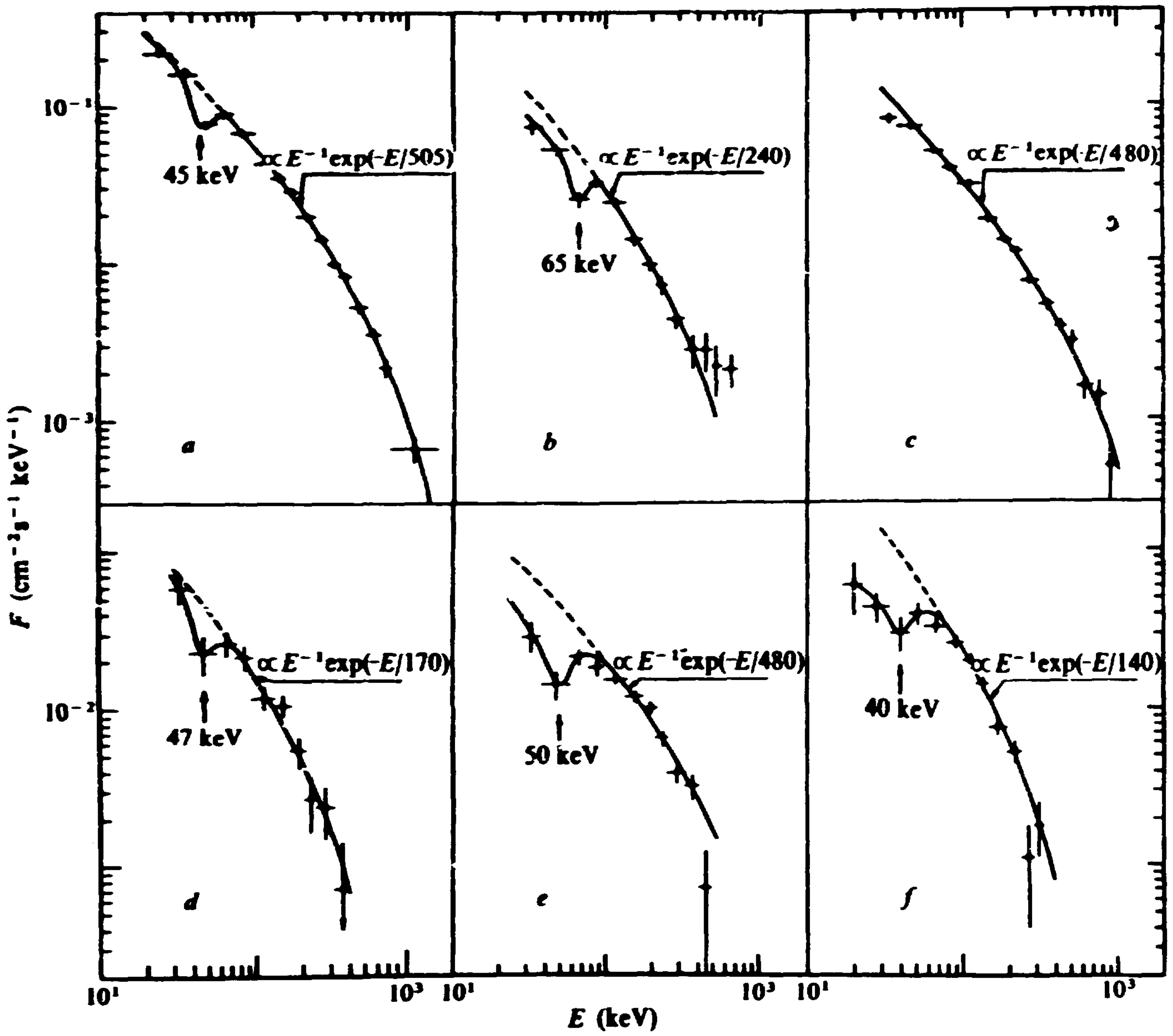
Eγ (keV)

APOLLO 16 GAMMA RAY EVENT
ENERGY SPECTRUM





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10^{-3}
10^{-2}
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a
65 keV
$\propto E^{-1}\exp(-E/240)$
b
$\propto E^{-1}\exp(-E/480)$
c
47 keV
$\propto E^{-1}\exp(-E/170)$
d
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$\propto E^{-1}\exp(-E/480)$
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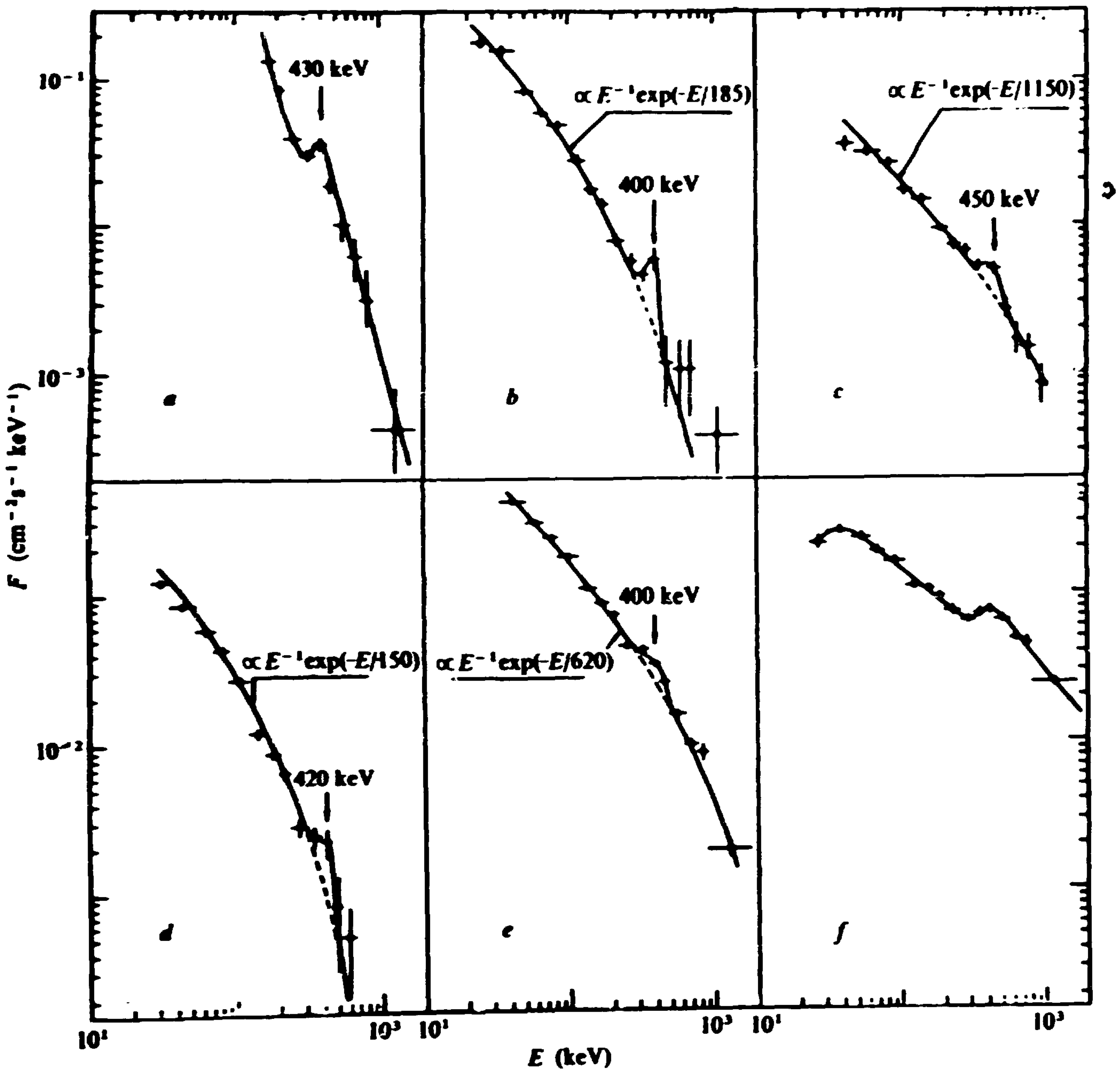
f
10^1
10^3
E (keV)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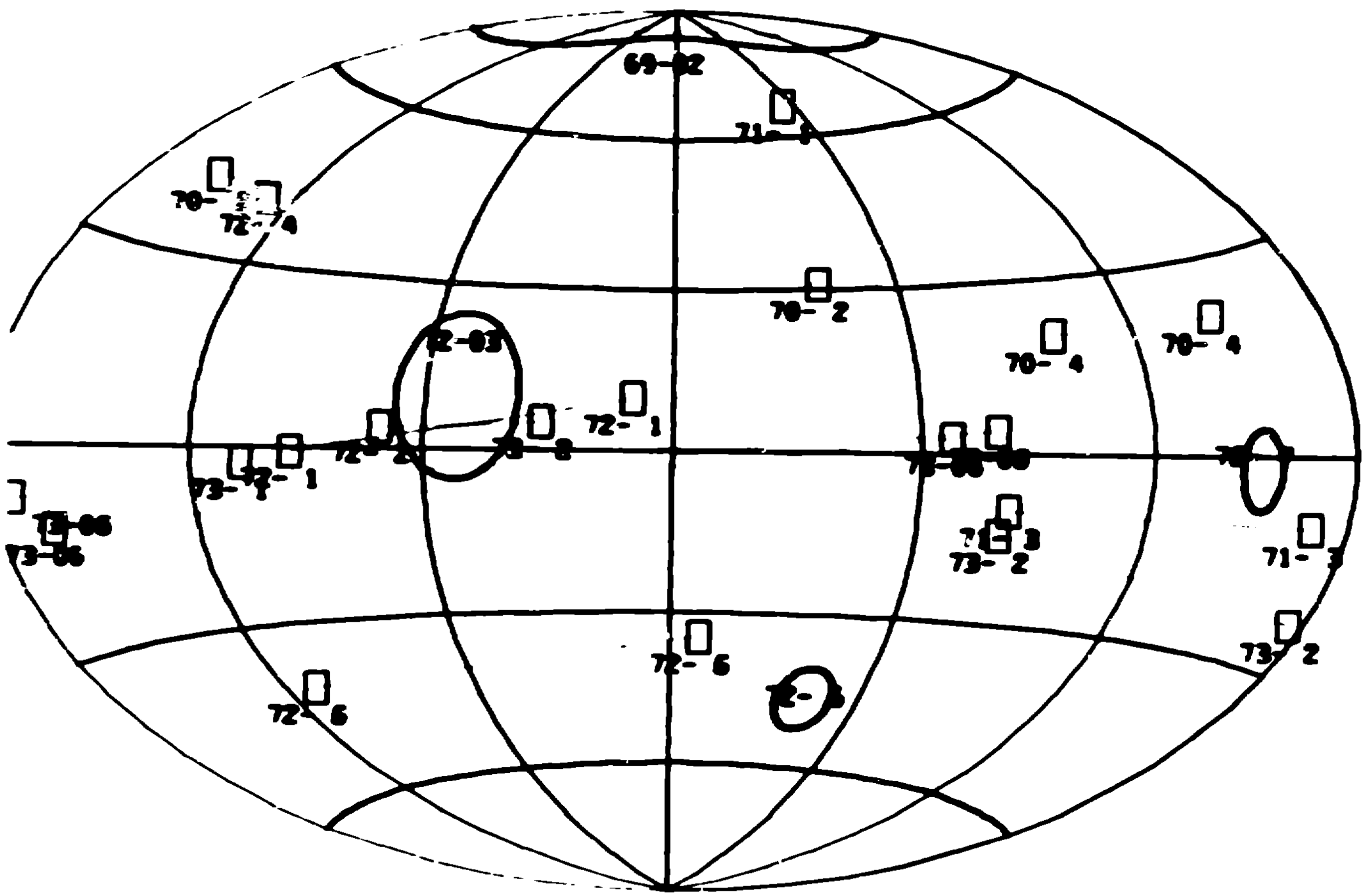
400 keV
∝ E⁻¹exp(−E/1150)
450 keV
a
b
c
∝ E⁻¹exp(−E/150)
420 keV
∝ E⁻¹exp(−E/620)
400 keV
d
e
f
F (cm⁻²s⁻¹ keV⁻¹)
E (keV)
10¹
10³

DISTRIBUTION OF TRANSIENT G-RAY SOURCES



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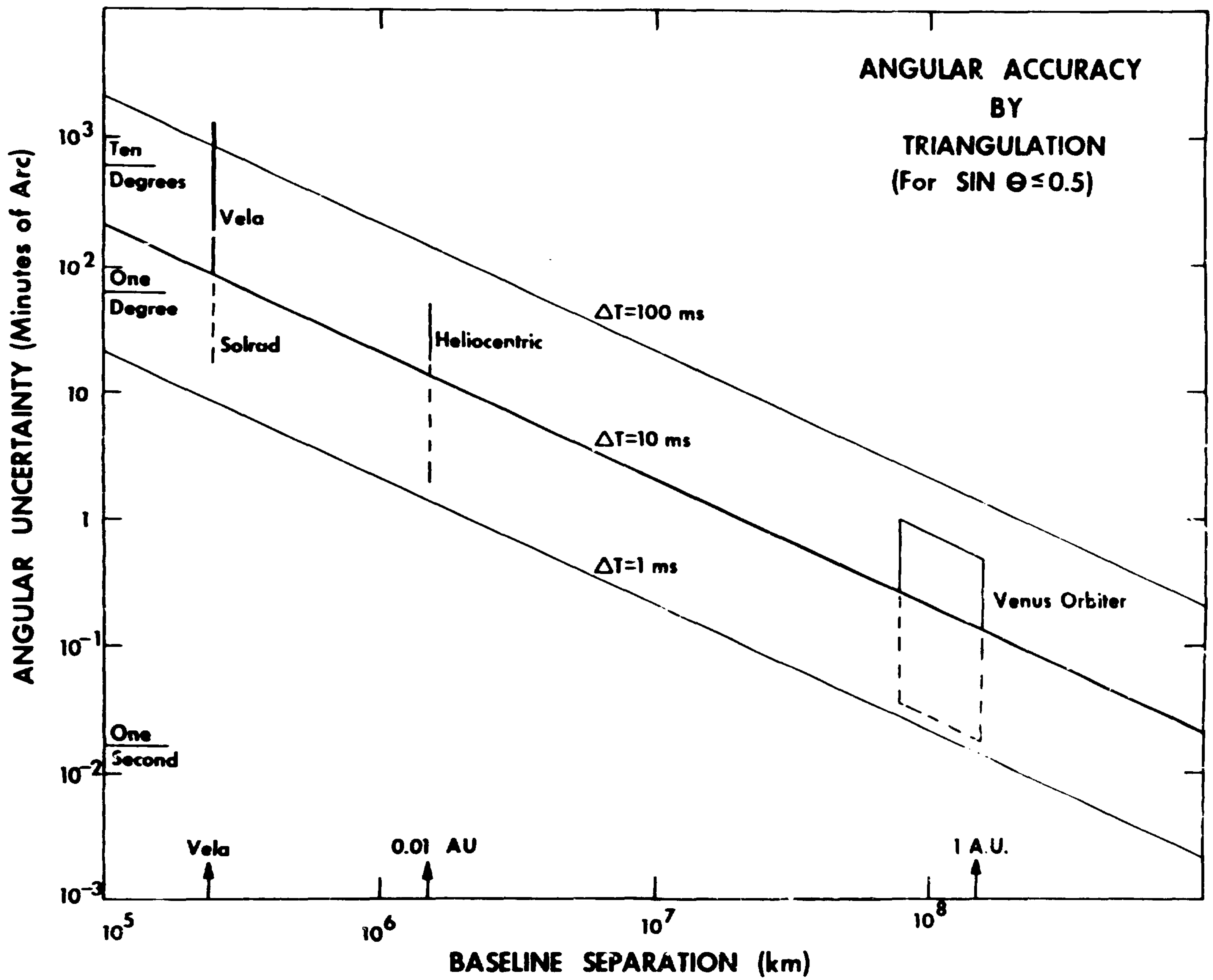
CENTERED AT L=0, B=0 (GALACTIC COORDINATES)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10^-1
10^-2
10^-3
10^5
10^6
10^7
10^8
Ten Degrees
One Degree
One Second
Vela
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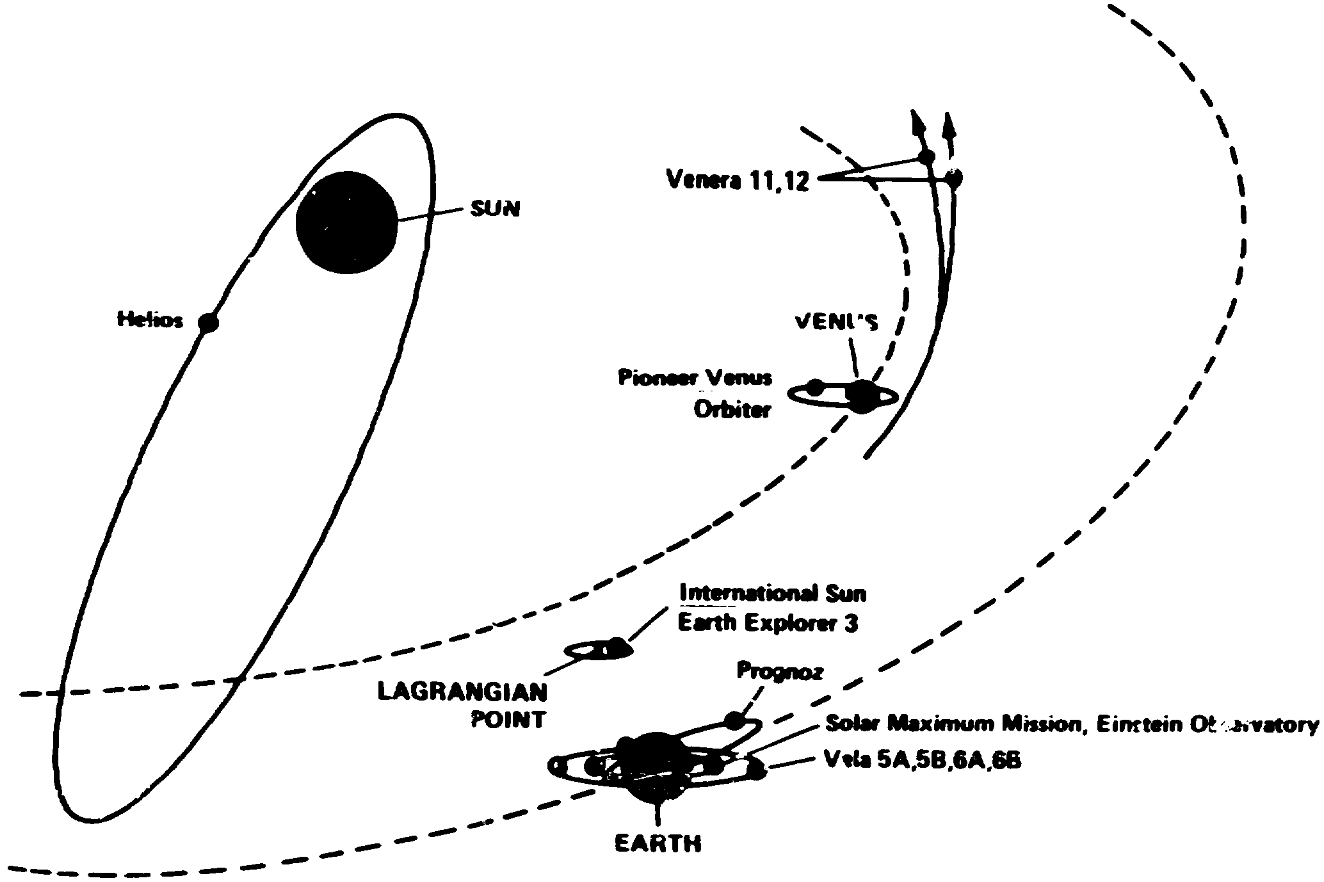
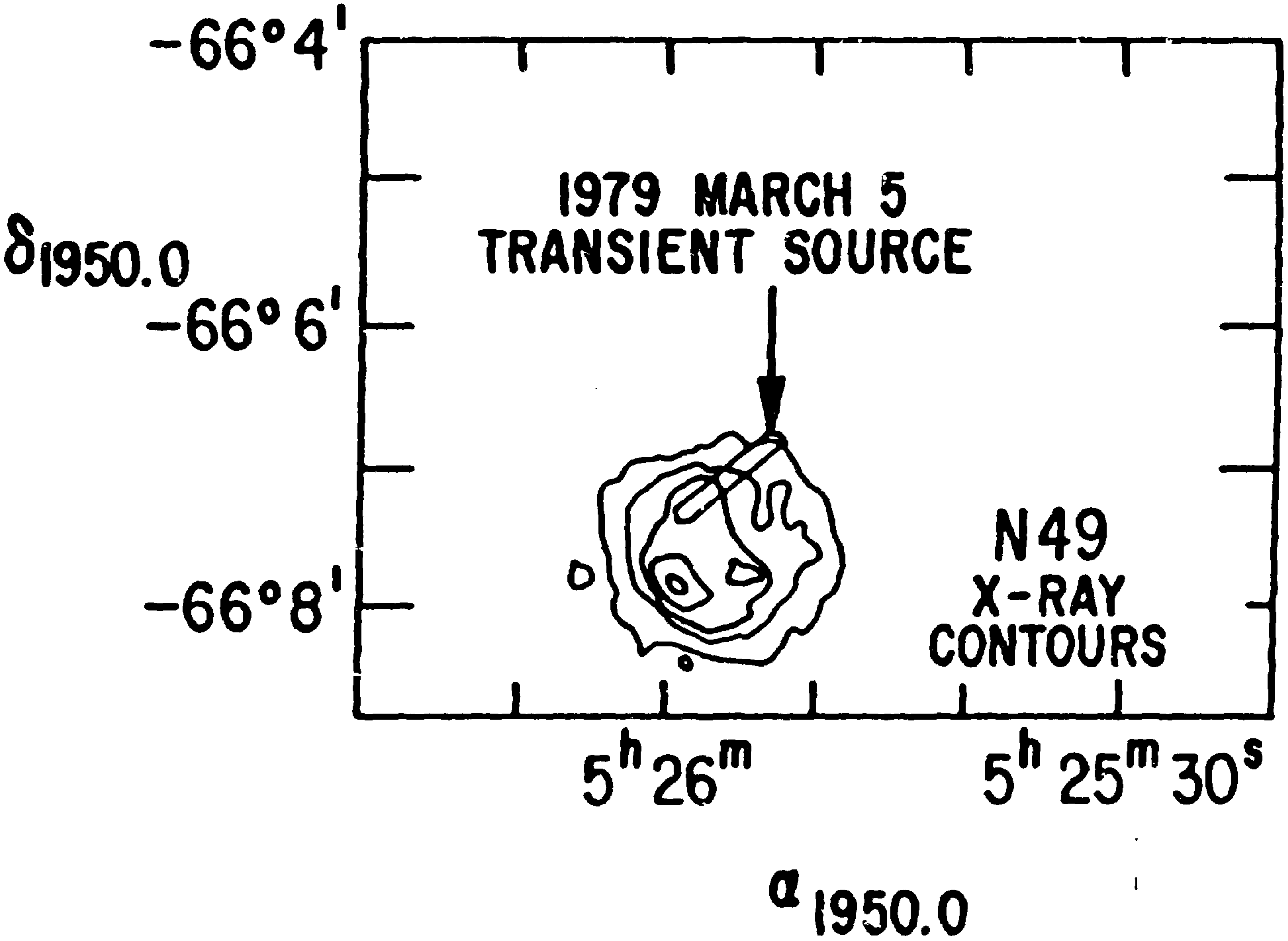
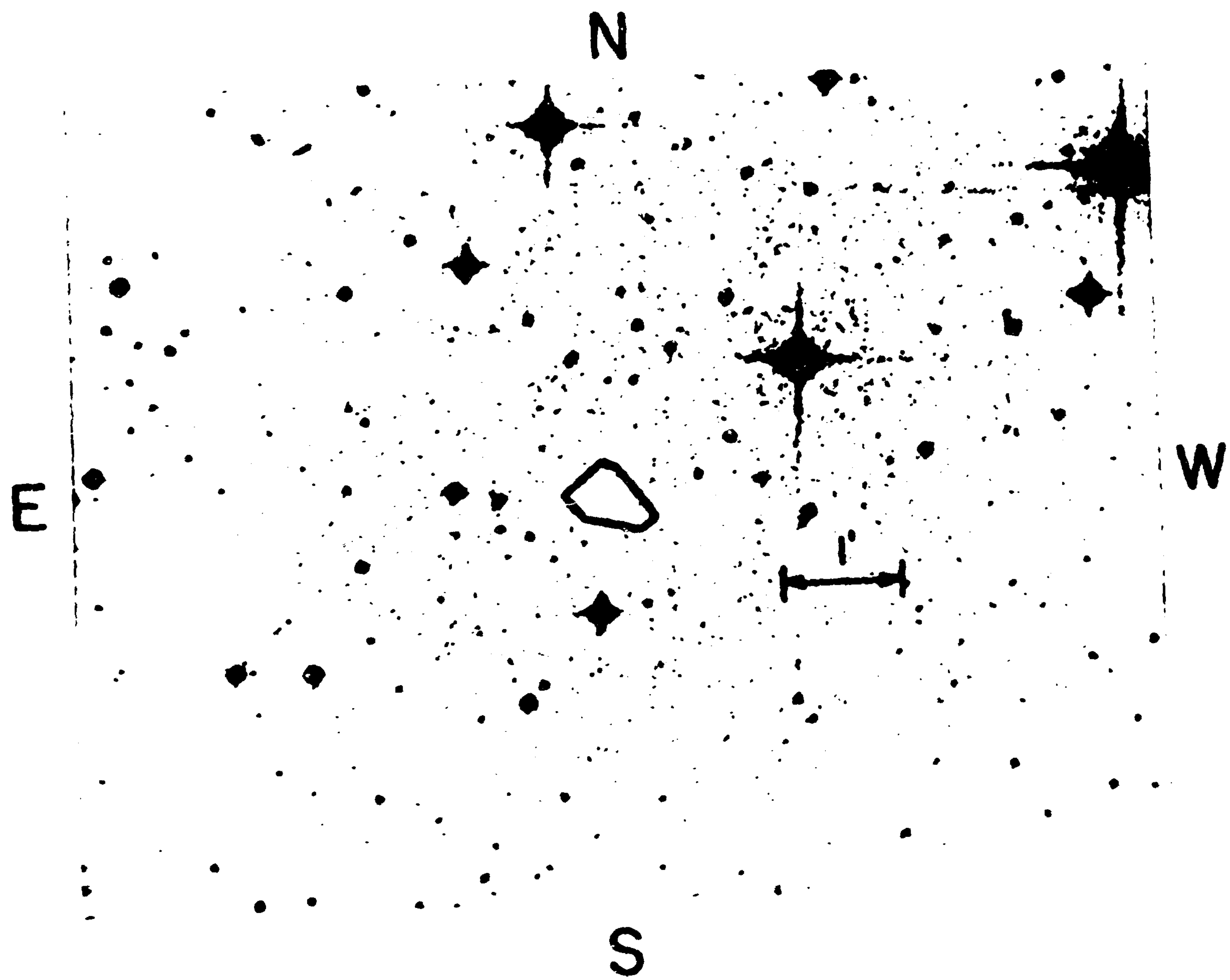
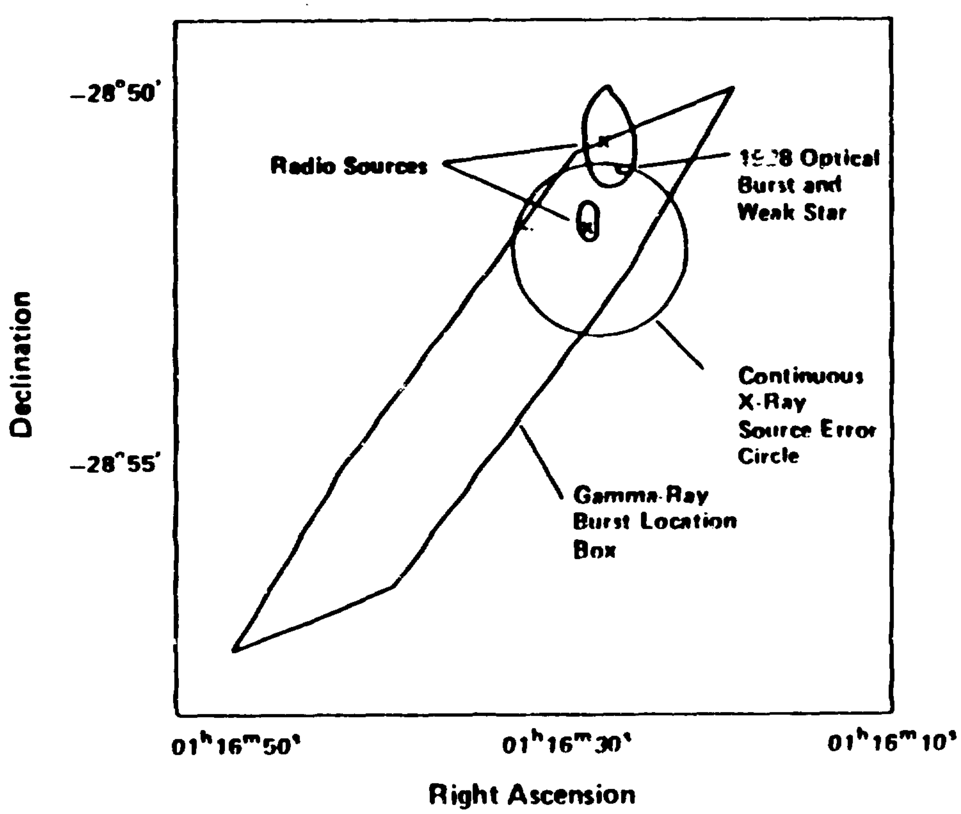




1979 MARCH 5
TRANSIENT SOURCE
N49
X-RAY
CONTOURS
$\delta_{1950.0}$
$-66^\circ4'$
$-66^\circ6'$
$-66^\circ8'$
5^h26^m
$5^h25^m30^s$
$\alpha_{1950.0}$


N
E
W
S
1'


−28°50′
−28°55′
Declination
Radio Sources
1928 Optical
Burst and
Weak Star
Continuous
X-Ray
Source Error
Circle
Gamma-Ray
Burst Location
Box
01h16m50s
01h16m30s
01h16m10s
Right Ascension